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Projections of change in key ecosystem indicators for planning and management of marine protected areas: An example study for European seas

Susan Kay*, Momme Butenschön

Plymouth Marine Laboratory, UK

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ABSTRACT

Marine Protected Areas (MPAs) are widely used as tools to maintain biodiversity, protect habitats and ensure that development is sustainable. If MPAs are to maintain their role into the future it is important for managers to understand how conditions at these sites may change as a result of climate change and other drivers, and this understanding needs to extend beyond temperature to a range of key ecosystem indicators. This case study demonstrates how spatially-aggregated model results for multiple variables can provide useful projections for MPA planners and managers. Conditions in European MPAs have been projected for the 2040s using unmitigated and globally managed scenarios of climate change and river management, and hence high and low emissions of greenhouse gases and riverborne nutrients. The results highlight the vulnerability of potential refuge sites in the north-west Mediterranean and the need for careful monitoring at MPAs to the north and west of the British Isles, which may be affected by changes in Atlantic circulation patterns. The projections also support the need for more MPAs in the eastern Mediterranean and Adriatic Sea, and can inform the selection of sites.

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1. Introduction

Marine protected areas (MPAs) are a key element of strategies to protect coastal and shelf sea ecosystems in many parts of the world. They have been set up to maintain biodiversity, restore damaged ecosystems, ensure sustainable development and to protect a representative range of species and habitats (OSPAR Commission, 2013). Creation of MPAs was spurred by the 1992 Convention on Biological Diversity (CBD) and the current CBD target is for 10% of coastal and marine areas to be conserved by well-managed, ecologically-representative and well-connected protected areas by 2020 (Gabrié et al., 2012). As well as protecting biodiversity, MPAs can help to ensure the long-term sustainability of fisheries (Weigel et al., 2014) and preserve coastal and marine sites of socio-cultural value (Börger et al., 2014; Gabrié et al., 2012).

Marine areas worldwide, and particularly coastal areas, face many anthropogenic threats, arising from both local and non-local sources (Halpern et al., 2008). Marine Protected Areas can reduce threats from local sources such as fishing and recreation, but they remain vulnerable to impacts from riverborne nutrients sourced from the wider area and from global climate change. These exogenous, unmanaged drivers (Elliott et al., 2015) will affect MPAs regardless of their protected status, and effective planning and management requires an understanding of the change in local environmental conditions that they are likely to produce. Environmental change may make an MPA unsuited to the purpose for which it was set up, for example if conditions are no longer appropriate for a target species. Management regulations which are framed in terms of current conditions may no longer be appropriate if climate change affects what can be considered 'normal' for a given system – the shifting baseline effect (Elliott et al., 2015).

A number of studies have looked at the potential impact of climate change on MPAs and suggested ways in which MPAs can be designed and managed so as to limit the risk of ecosystem damage. Results include guidance produced for North American MPAs (Brock et al., 2012; ICES, 2011), for coral reefs and other tropical seas (Green et al., 2014) and for the Mediterranean (Otero et al., 2013). These studies are based on the expected response of organisms and ecosystems to rising temperatures (e.g. O'Connor et al., 2007; Marras et al., 2015; Hoegh-Guldberg and Bruno, 2010). Studies

* Corresponding author. Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth PL1 3DH, UK.
E-mail address: suka@pml.ac.uk (S. Kay).

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are beginning to show how the effect of other variables can interact with temperature changes, making assessments based only on temperature changes inadequate e.g. (Deutsch et al., 2015; Muir et al., 2015).

There has been little use of model projections of future conditions for the planning of marine protected areas (Levy and Ban, 2013; Makino et al., 2014) and those that do tend to use projections of surface temperature only. They also rely on global climate models (GCMs) with resolutions typically 50 km or more. Satellite data provides higher resolution, but does not by itself give information about future conditions (Chollett et al., 2014). As future projections downscaled to the regional level become more common, their potential for MPA planning and management can be developed.

Other studies have used a species-based approach to investigate the threat to biodiversity from climate change. Jones et al. (2013) used species distribution models to project changes in the range of 17 fish species in the North Sea. The species distribution models made use of a number of variables taken from GCMs, and so they go beyond projections based only on temperature. Jones et al. considered the use of their model results to judge the change in habitat suitability of protected areas, but they suggest that this would need to be done on a species by species and area by area approach: there is no simple pattern of change across areas.

Another anthropogenic threat to marine ecosystems comes from riverborne influxes of nitrates and phosphates. Eutrophication associated with high river nutrient loadings has long been a problem in parts of the North Sea and the Mediterranean (Coll et al., 2010; Langmead et al., 2007). Reduction of this threat requires changes in land use and water treatment upstream, perhaps in a different jurisdiction. Model projections have been more widely used to investigate this issue and the consequences of possible mitigation actions (e.g. Lenhart et al., 2010; Skogen et al., 2014). In practice, MPAs are experiencing the combined effects of climate change and river nutrient loadings and models can be used to investigate the interaction between these stressors.

Here we show how a regional model, downscaled from global data, can be used to make projections of change in a number of key ecosystem indicators resulting from changes in climate and river nutrient loadings. We present spatially-aggregated results that give an overview of projected change in conditions in a selected area under two different scenarios: these provide a starting point from which managers and planners can go on to investigate possible actions, such as increased protection through changes in local management (Micheli et al., 2012), an extension of the MPA area, creation of other MPAs nearby to give a more robust network or perhaps future relocation of the MPA to an area where future conditions are more appropriate for its purpose. The model projections include both physical and biogeochemical indicators – temperature, salinity and mixed layer depth, nutrient concentrations, dissolved oxygen, surface chlorophyll, primary production and zooplankton biomass. They thus give a richer view of conditions in an area of interest than is possible with use of a single indicator, and they demonstrate how resilient a given area is to climate change, i.e. whether the changes occurring in this area are significantly altering habitat conditions. They also illustrate how susceptible an area is to policy change by showing how much the projected changes differ between the contrasting scenarios. The examples given are for European seas, but the methods used are general and could be applied anywhere in the world – and to any spatial area of interest, not just to MPAs.

Our study areas are the Mediterranean Sea and the North-East Atlantic (Fig. 2). These seas encompass a wide range of temperate marine conditions and include coastal, shelf sea and deep water areas. The Mediterranean is largely enclosed, being connected to the Atlantic only via a narrow strait at the western edge. The sea has a long northern coastline which limits the poleward movement of species in a warming climate. Surface temperatures are typically 16–28 °C (Butenschön and Kay, 2013). The North-East Atlantic comprises the shallow North Sea and English Channel, to the east and south of the British Isles respectively, as well as the deeper waters to the west. Unlike the Mediterranean, it is open to influence from the wider Atlantic Ocean and has no land mass to the north. Surface temperatures are cooler and more variable than in the Mediterranean, from near-freezing up to 20 °C (Butenschön and Kay, 2013).

Networks of protected areas have been set up in both seas. In 2012 Mediterranean MPAs covered an area of about 115,000 km^2, about 4.6% of the Sea's area. However, three quarters of this was in a single MPA, the Pelagos Sanctuary for Mediterranean Marine Mammals (Gabrié et al., 2012). The network is largely restricted to small coastal sites and there are relatively few sites on the southern and eastern shores. The North-East Atlantic has a better-developed MPA network: in December 2012 there were 333 MPAs, covering an area of 700,000 km^2, 5% of the entire OSPAR area and 22% of coastal waters (OSPAR Commission, 2013). These range from coastal zones to larger shelf sea areas and deep sea areas around seamounts. Fig. 2 shows the sample of MPAs which are included in the current study and their main features are listed in Table 1.

The scenarios presented here have been produced using projections of marine physics and biogeochemistry and the lower trophic level ecosystem. These projections were developed under the EU project VECTORS (Austen et al., 2018) and have delivered the baseline for the socioeconomic scenarios used in this project (Groenveld et al., 2018). They have been run for two contrasting future scenarios of climate change and river nutrient levels for the period 2040–2049, as well as a reference run for 2000–2009. The two scenarios were chosen to represent more and less sustainable situations of economic development – lower/higher greenhouse gas emissions and river nutrient levels. The projections thus give an envelope of potential conditions in the 2040s.

2. Methods

2.1. The numerical model

Modelling was carried out using the biogeochemical and lower trophic level model ERSEM (Blackford et al., 2004; Butenschön et al., 2016) coupled to the hydrodynamic shelf sea model POLCOMS (Holt and James, 2001). Both have a long history of use in modelling the North-East Atlantic system e.g. (Allen et al., 2007; Siddorn et al., 2007) and global shelf seas (Barange et al., 2014; Blanchard et al., 2012; Holt et al., 2009). For the current study the model system was designed to be consistent across all marine areas included: the same model resolution (0.1°, about 6–11 km) and the same sources of forcing data. Separate domains were used for the Mediterranean and the North-East Atlantic. A full description of the model set-up is given in Butenschön and Kay (2013); a brief summary is given here.

ERSEM includes three size-class based functional types of phytoplankton plus diatoms, three functional types for zooplankton, bacteria, three size classes of particulate organic matter, dissolved and semi-labile organic matter and the inorganic components nitrate, phosphate, silicate, dissolved oxygen and DIC (Fig. 1). The cycles of the main chemical constituents of the system, i.e. carbon, nitrogen, phosphate and silicate, are resolved explicitly, with variable stoichiometry in the organic components, and the model also includes microbial dynamics. For the North-East Atlantic the ERSEM benthic model was used to model the seabed subsystem, but this was not suitable for Mediterranean conditions

Table 1
Marine protected areas included in this study, with location and size features.

Name of MPA	Sea	Latitude (°N)	Longitude (°E)	Depth (m)	Reserves area (km^2)	Modelled area (km^2)
Alboran Island	W Med	36.0	−3.0	902	264	300
Evro Delta	W Med	40.6	0.8	52	357	281
Garraf Coast	W Med	41.2	1.9	420	265	372
Migjorn de Mallorca	W Med	39.3	3.0	370	223	861
Gulf of Lion	W Med	42.7	3.5	244	4009	3997
Calanques	W Med	43.1	5.4	647	435	1263
Pelagos Sanctuary	W Med	42.7	8.8	1458	87,305	82,762
Iles Kneiss	Central Med	34.3	10.3	13	160	408
Isole Egadi	Central Med	38.0	12.2	338	540	975
Kornati	Adriatic	43.8	15.4	102	166	893
Capo Rizzuto	Central Med	39.0	17.1	537	147	481
Porto Cesareo	Central Med	40.2	17.9	135	167	283
Alonissos-Northern Sporades	Aegean	39.3	24.1	429	2070	2297
Sallum Gulf	E Med	31.6	25.6	260	327	1052
Gokova	E Med	36.9	27.7	266	820	396
Israeli coastal sites	E Med	32.7	34.8	511	7	2912
East Rockall Bank	NE Alantic	57.7	−13.4	886	3695	3170
Hovland Mound Province	NE Alantic	52.2	−12.8	754	1090	1060
Stanton Banks	Celtic Seas	56.2	−7.9	93	817	755
Haig Fras	Celtic Seas	50.3	−7.7	83	481	474
Wyville Thomson Ridge	NE Alantic	60.0	−6.8	617	1740	1730
Iroise	Celtic Seas	48.2	−5.0	73	3428	3105
Luce Bay and Sands	Celtic Seas	54.7	−4.7	24	479	71
Cardigan Bay	Celtic Seas	52.3	−4.6	23	953	453
Moray Firth SAC	North Sea	57.9	−3.6	30	1513	575
Liverpool Bay	Celtic Seas	53.5	−3.5	16	1703	660
Wight-Barfleur Reef	English Channel	50.3	−1.5	54	1373	1263
Pobie Bank Reef	North Sea	60.5	−0.3	91	966	973
Margate and Long Sands	North Sea	51.6	1.4	11	649	690
Norfolk Sandbanks and Saturn Reef	North Sea	53.4	2.1	25	3606	3684
Dogger Bank	North Sea	54.9	2.2	27	12,340	12,229
Vlaamse Banken		51.3	2.6	17	1182	1003
Noordzeekustzone	North Sea	53.2	5.2	14	1416	1089
Sylt.Aussenr.-Oestl.Dt.Bucht	North Sea	54.8	7.4	25	5595	5693
Gule Rev	North Sea	57.3	8.2	67	473	334
Wadden Sea National Park	North Sea	54.5	8.4	9	4602	2027

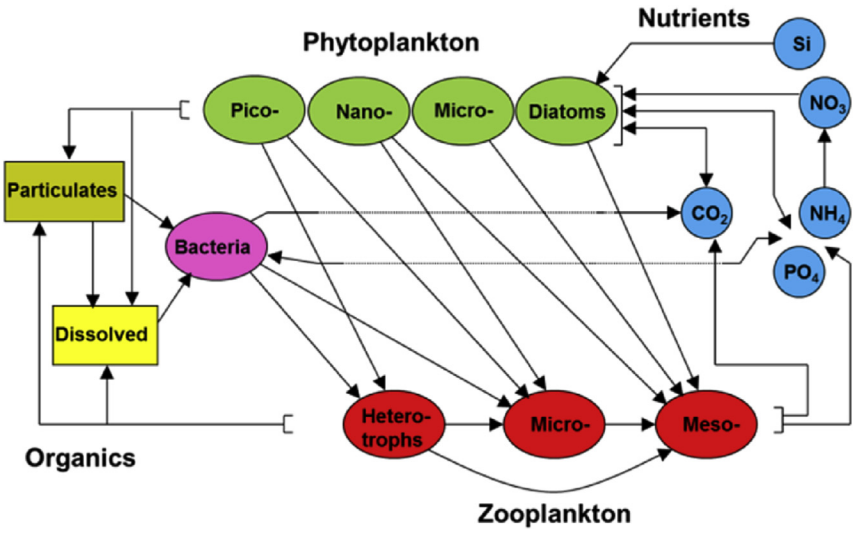


Fig. 1. The ERSEM pelagic food web.

and instead a simple remineralisation closure scheme was used: this returns benthic organic matter as inorganic component through a fixed rate.

External conditions were applied to the model at the atmospheric and open-ocean boundaries and at river mouths. For the present-day model run, forcing data was derived from reanalysis data: ERA Interim meteorological data (Dee et al., 2011) at the atmospheric boundary and GLORYS data (Ferry et al., 2012) at the open ocean boundary. River outflow volumes and nutrient levels were taken from the Global *NEWS* database (Seitzinger et al., 2005). River inputs were assumed to be constant throughout the year.

For each run, the model was spun up for 5 years before starting the 10 year run. The reanalysis-driven run was for 2000–2009, future projections for 2040–2049.

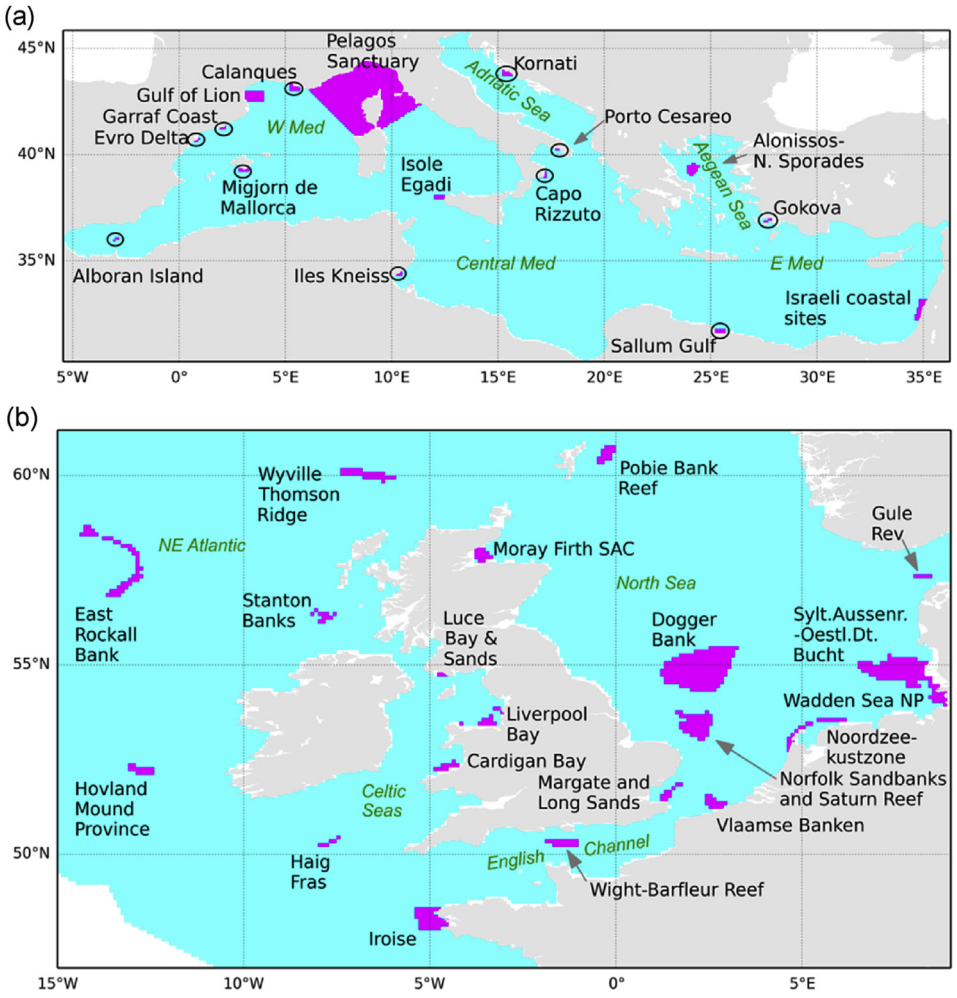


Fig. 2. MPAs selected for analysis, (a) Mediterranean and (b) North-East Atlantic. MPAs are shown in pink, black circles are used to highlight the smaller MPAs. The sea area shown in white at the bottom left of (b) is outside the model domain. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Scenario setup and downscaling of forcing data

Two future scenarios were modelled: these were chosen to represent opposing socioeconomic environments and mitigation strategies and hence to illustrate the range of response of the system. They are broadly based on the SRES scenarios A2-National Responsibility and B1-Global Community (Nakićenović and Swart, 2000).

- In the National Responsibility (NR) scenario, development and management decisions are generally based on a nation's self-interest. Greenhouse gas emissions are relatively high and limited efforts have been made to reduce pollutants in rivers.
- Under the Global Community (GC) scenario international co-operation and environmental sustainability are higher priorities. Mitigation strategies have kept greenhouse gas emissions relatively low and river pollution is coming under control.

Forcing data for these future scenarios was developed from the present-day values using a delta method: the fine-scale temporal and spatial variation from the present-day forcing data was applied to the coarser scale conditions taken from a global climate model (GCM), thus creating a plausible decade of conditions consistent with the GCM but at higher resolution. Delta downscaling allows regional-level data to be generated from a GCM without the cost of a full regional climate model run, but it decouples the fine-scale variation from the larger patterns in the GCM so there is a risk of inconsistency: the resulting data set is physically plausible rather than physically consistent and small-scale variation associated with climate change is not captured.

The GCM used was the coupled atmosphere-ocean model ECHAM5/MPIOM (Jungclaus et al., 2006); this model gives comparable simulations of current conditions to other models used in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4, Randall et al., 2007) and its carbon sensitivity is in the middle of the range of the IPCC AR4 models. This GCM can thus be seen as typical of the models available at the time the data was used, and use of two contrasting climate change scenarios, A2 and B1, means that a range of possible futures has been explored. It was beyond the scope of this work to investigate the variation produced by using different GCMs, but that would be desirable in a larger study.

The GCM provided monthly data at resolution 1.875°. Two types of modification were used to generate the downscaled data: additive [1] and multiplicative [2]:

$$\boldsymbol{\Psi}_{\boldsymbol{future}}(\mathbf{x},t) = \boldsymbol{\Psi}_{\boldsymbol{RA}}(\mathbf{x},t) + \left[\boldsymbol{M}_{\boldsymbol{future}}(\mathbf{x}',t') - \boldsymbol{M}_{\boldsymbol{present}}(\mathbf{x}',t')\right] \quad [1]$$

$$\boldsymbol{\Psi}_{\boldsymbol{future}}(\mathbf{x},t) = \boldsymbol{\Psi}_{\boldsymbol{RA}}(\mathbf{x},t)^{*}\left[\frac{\boldsymbol{M}_{\boldsymbol{future}}(\mathbf{x}',t')}{\boldsymbol{M}_{\boldsymbol{present}}(\mathbf{x}',t')}\right] \quad [2]$$

where Ψ_{RA}, Ψ_{future} are the present-day and future forcing data, M_{present} and M_{future} the values from the GCM output. ($\mathbf{x}$,t) represents a point in the forcing data, ($\mathbf{x}'$,t') is used for the GCM data grid, which is typically at a different resolution and interpolated to match the forcing data grid.

For each variable, linear regression between future and present climate model data across all time and space points was used to select which method to use:

$$M_{future} = k^{*}M_{present} + X \quad [3]$$

In cases where the regression showed a strong correlation with $k \approx 1$ and $X \neq 0$ an additive method was used; where X was close to 0 a multiplicative method gave a better fit to the model's behaviour. The additive method was used for solar and thermal radiation, temperature (air and sea), salinity, pressure and wind and current components, the multiplicative method for cloud cover, precipitation and relative humidity.

For all variables except precipitation, the spatial resolution of the climate model was retained, while the data for each month was averaged over the ten year period to give a monthly climatology for the calculations of the deltas. This choice was preferred over the full temporal resolution to avoid spurious trends due to interannual/decadal variability that remain unidentifiable in short time-slice experiments like these. However, intra-annual (e.g. seasonal) changes between the present and future GCM runs have been retained. In the case of precipitation, averaging only over the time period led to some low values in the present-day model data and hence unrealistically high future values when using equation [2]. The problem was resolved by using model data averaged over the whole domain to smooth the input; this means that spatial variation in rainfall derive only from the original reanalysis data and not from the climate model.

Atmospheric CO_2 levels were set at 505 ppm for A2 and 475 ppm for B1, based on IPCC model projections (IPCC, 2001).

The effect of these changes was an increase of air temperatures at sea level in the region of 1 °C with respect to present day for the NR scenario, and about 0.7 °C for GC. Wind speeds showed no change in the Mediterranean, but a slight rise in the North-East Atlantic, of the order of 1 m s^{-1} for both scenarios. The result in the modelled outputs was an increase in sea surface temperature in the Mediterranean of 0.6–1.0 °C under the NR scenario and 0.4–0.8 °C under the GC scenario; for the NE Atlantic shelf seas the increases were 0.7–1.0 °C under NR and 0.5–0.9 °C under GC (Fig. 4). These values are consistent with other modelling studies, which have looked at longer time scales: projected end-century sea surface temperature increases for the Mediterranean are 2.5–3.0 °C under the A2 scenario and 1.7 °C for the B1 scenario (Adloff et al., 2015) and for the NE Atlantic shelf 2–4 °C under the A1B scenario (Holt et al., 2010).

River flow volumes were not changed from their present-day values, because consistent hydrological projections were not available for both seas. In a sensitivity study for the Mediterranean, Adloff et al. (2015) found that river flow volume had a much smaller effect on model evolution than other drivers. River flows affect salinity and hence stratification and transport within a few grid cells of river mouths, but in other areas forcing from precipitation is likely to be more important (Holt et al., 2010). Values for river nitrate and phosphate levels were adjusted based on the assessments given in the European Lifestyles and Marine Ecosystems report (Langmead et al., 2007). Under the NR scenario nitrates and phosphates were both increased by 60% for the Mediterranean; nitrates increased by 30% and phosphates were unchanged for the North-East Atlantic. Under the GC scenario there was no change in the Mediterranean; nitrates were unchanged and phosphates decreased by 30% for the North-East Atlantic.

Nitrate and phosphate values at the ocean boundary were set using the World Ocean Atlas climatological values (Garcia et al., 2010). These were not changed for the future scenarios as no biogeochemical information was available from the GCM.

2.3. Site description

The model outputs were used to calculate present-day and future scenario values for a range of indicators, for a set of MPAs chosen to include all parts of each sea (Fig. 2). Smaller MPAs were avoided where possible, as the model is less reliable at the 6–11 km scale of the model grid (see Section 3.1). However, in areas where no large MPAs exist, some smaller ones were included, and a larger area of sea including the MPAs was modelled (Table 1). In the case of the Israeli coast a single area covering several small MPAs was used. No attempt was made to resolve spatially within the area of a single MPA, all results are presented for entire MPAs only.

2.4. Data analysis and presentation

Projected change in the MPAs is presented in the form of tables showing the size of the difference between present and future values for a number of key ecosystem indicators (Tables 2 and 3). In each case the difference was calculated for each of the ten years of the model run:

$$size\ \ of\ \ change = \frac{1}{n}\sum_{i=1}^{n}\left(I^{i}_{future} - I^{i}_{present}\right) \quad [4]$$

where I^{i}_{future} represents the mean value of the indicator for month i of the 2040s, averaged over the MPA, and $I^{i}_{present}$ represents values for the 2000s. For most indicators all 12 months of each year were used ($n = 120$); for winter nutrients only the mean for November–February of each year ($n = 40$) and for summer chlorophyll the mean for March to October ($n = 80$); these season definitions have been used to match those in the OSPAR criteria for eutrophication status (OSPAR Commission, 2010). The tables are shaded to show the mean difference relative to the range of values seen in the 120 months of the present-day run: this gives an index of change which can be compared across the different indicators.

$$index\ \ of\ \ change = \frac{size\ \ of\ \ change}{\max(I_{present}) - \min(I_{present})} \quad [5]$$

Model cells where the difference is not statistically significant ($p > 0.05$) are coloured white and the difference given as grey text. Statistical significance was based on a t-test of the null hypothesis that current and future conditions are the same, using the 10 years of the model run as a sample. The delta method of producing the model forcing means that the years of the present-day and future runs are not completely independent: for example, the small-scale variation in 2041 is based on that in 2001. However the large-scale variation provided by the GCM is not related in this way and so the data are neither completed paired nor completely independent. The p-values presented are for a t-test of independent data, which would tend to underestimate rather than overestimate the

Table 2
Difference 2040s–2000s for ecosystem indicators for Mediterranean MPAs under (a) National Responsibility scenario (b) Global Community scenario. Differences shown are for the annual mean or minimum monthly value, as shown in the column headings, except for winter nutrients which are the mean for Nov–Feb and summer chlorophyll which is the mean for March–Oct. Cells are coloured by an index of change, defined as the ratio of the change to the range of values seen in the present-day model run (equation (5)). White cells are used where the change is not statistically significant (i.e. $p > 0.05$). See section 2.4 for more details on how the changes are calculated.

(a)

	mean surface T (°C)	max surface T (°C)	min surface T (°C)	mean bottom T (°C)	mean netPP ($mgCm^{-2}\,d^{-1}$)	mean column Zc ($mg\,C\,m^{-2}$)	mean summer Chl ($mg\,chl\,m^{-3}$)	min bottom O_2 ($mmolm^{-3}$)	mean winter N ($mmol\,m^{-3}$)	mean winter P ($mmol\,m^{-3}$)	mean winter Si ($mmol\,m^{-3}$)	mean winter N:P ratio	mean surface S (psu)	mean MLD (m)
Alboran Island	0.53	0.57	0.42	0.19	36.9	45.0	-0.041	-1.15	-0.41	-0.025	-0.17	-0.41	-0.26	-3.13
Evro Delta	0.69	1.09	0.50	0.46	33.3	36.1	0.012	-2.29	1.24	0.009	-0.04	6.81	-0.01	-0.32
Garraf Coast	0.67	0.95	0.43	0.31	27.0	16.5	0.006	-2.65	0.15	-0.000	-0.08	1.25	-0.02	-7.00
Migjorn de Mallorca	0.66	0.74	0.47	0.24	-19.1	-60.1	-0.029	0.25	-0.15	-0.017	-0.15	7.15	0.01	-4.25
Gulf of Lion	0.71	0.93	0.41	0.41	43.1	56.2	0.020	-1.67	0.41	0.008	0.00	1.66	-0.03	-7.50
Calanques	0.65	0.86	0.39	0.23	28.0	21.0	0.023	0.76	0.10	-0.003	0.06	2.64	-0.04	-28.81
Pelagos Sanctuary	0.65	0.71	0.37	0.21	9.4	7.6	-0.002	-0.31	-0.09	-0.010	-0.07	2.94	-0.03	-22.72
Iles Kneiss	0.71	0.78	0.77	0.71	61.2	48.9	0.065	-2.01	0.41	0.220	0.07	-2.84	-0.09	0.05
Isole Egadi	0.63	0.80	0.39	0.40	2.0	20.6	-0.024	-2.79	0.11	-0.002	0.06	2.95	-0.04	-4.65
Kornati	0.82	0.98	0.58	0.63	40.5	36.9	0.020	-4.51	1.46	0.032	0.01	3.25	0.04	-0.72
Capo Rizzuto	0.74	0.83	0.52	0.27	21.5	34.1	0.009	-1.97	0.51	-0.002	-0.29	5.54	0.06	-15.67
Porto Cesareo	0.75	0.86	0.48	0.46	59.5	84.5	0.037	-3.04	0.42	-0.009	-0.25	4.02	0.04	-2.55
Alonissos-Northern Sporades	0.66	0.96	0.55	0.54	111.2	109.1	0.099	-2.51	1.83	0.111	0.10	0.58	0.04	1.18
Sallum Gulf	0.61	0.70	0.44	0.27	13.8	93.7	-0.001	-1.49	0.02	-0.001	0.05	2.89	-0.06	-3.32
Gokova	0.65	0.70	0.48	0.32	31.5	46.2	0.009	-1.13	0.10	-0.005	0.05	4.67	-0.00	-4.99
Israeli coastal sites	0.69	0.87	0.56	0.26	86.5	83.2	0.042	-2.60	0.10	0.007	-0.84	-0.96	-0.01	0.12

index of change: 2.0, 1.6, 1.2, 0.8, 0.4, 0.0, −0.4, −0.8, −1.2, −1.6, −2.0

(b)

	mean surface T (°C)	max surface T (°C)	min surface T (°C)	mean bottom T (°C)	mean netPP ($mgCm^{-2}\,d^{-1}$)	mean column Zc ($mg\,C\,m^{-2}$)	mean summer Chl ($mg\,chl\,m^{-3}$)	min bottom O_2 ($mmolm^{-3}$)	mean winter N ($mmol\,m^{-3}$)	mean winter P ($mmol\,m^{-3}$)	mean winter Si ($mmol\,m^{-3}$)	mean winter N:P ratio	mean surface S (psu)	mean MLD (m)
Alboran Island	0.38	0.47	0.39	0.21	55.3	16.9	0.005	-0.93	-0.41	-0.021	-0.19	-0.83	-0.37	-2.34
Evro Delta	0.57	0.72	0.54	0.42	-4.6	-27.6	-0.030	-2.54	0.02	-0.008	-0.07	2.80	-0.06	-0.48
Garraf Coast	0.57	0.69	0.50	0.34	2.3	-51.4	0.006	-2.16	-0.16	-0.015	-0.08	1.74	-0.06	-10.67
Migjorn de Mallorca	0.61	0.72	0.51	0.27	-17.9	-56.8	-0.025	2.49	-0.25	-0.019	-0.18	6.50	-0.04	-4.58
Gulf of Lion	0.56	0.67	0.39	0.39	7.8	47.8	0.001	-1.95	-0.06	-0.009	0.07	1.54	-0.10	-8.76
Calanques	0.50	0.56	0.44	0.25	34.1	0.3	0.034	1.90	-0.07	-0.011	0.06	3.22	-0.08	-30.97
Pelagos Sanctuary	0.55	0.54	0.43	0.22	9.5	11.9	0.005	0.45	-0.18	-0.015	-0.07	2.98	-0.07	-25.02
Iles Kneiss	0.77	0.77	0.81	0.77	17.6	-3.1	0.009	-2.05	-0.07	-0.036	0.01	0.15	-0.11	0.02
Isole Egadi	0.50	0.54	0.43	0.43	43.9	35.3	-0.018	-1.29	-0.01	-0.007	0.00	2.34	-0.13	-7.40
Kornati	0.75	1.00	0.64	0.65	-8.9	-49.7	-0.012	-3.35	-0.11	-0.021	0.08	1.13	0.05	-0.86
Capo Rizzuto	0.61	0.59	0.55	0.29	-1.1	-61.0	0.000	-0.07	-0.22	-0.020	-0.07	0.92	0.06	-15.16
Porto Cesareo	0.65	0.67	0.56	0.49	-1.8	-45.6	-0.003	-2.39	-0.35	-0.033	-0.11	1.60	0.05	-1.21
Alonissos-Northern Sporades	0.65	1.02	0.49	0.35	-2.3	-89.2	-0.026	-0.70	-0.08	-0.010	-0.27	0.04	0.02	4.15
Sallum Gulf	0.63	0.76	0.52	0.26	2.1	52.1	-0.014	-0.14	-0.02	-0.003	0.09	4.62	-0.09	-5.18
Gokova	0.64	0.86	0.38	0.31	-0.4	6.6	-0.004	-0.28	-0.03	-0.005	0.19	2.71	-0.02	-4.32
Israeli coastal sites	0.68	0.72	0.59	0.25	2.2	-7.4	0.008	-1.11	0.08	-0.000	-0.59	4.23	-0.05	1.59

index of change: 2.0, 1.6, 1.2, 0.8, 0.4, 0.0, −0.4, −0.8, −1.2, −1.6, −2.0

significance.

The indicators presented are:

- Temperature (T) – the mean surface and bottom-water values, and also the maximum and minimum surface values: changes in these could push local temperatures out of the acclimatisation range of some native species or into the range for non-native competitors (Hoegh-Guldberg and Bruno, 2010).
- Biological indicators – net primary production (netPP), mean zooplankton biomass for the water column (Zc) and mean surface chlorophyll-a (Chl) for the growing season.
- Dissolved oxygen (O_2) at the bottom level: this can be affected by temperature change and low values can also result from eutrophication
- Dissolved nutrients – winter mean surface nitrate (N), phosphate (P) and silicate (Si); also the mean winter N:P ratio: these can be indicators of eutrophication
- Other physical indicators – surface salinity (S) and mixed layer depth (MLD): these can indicate changes in the water column structure

3. Results

3.1. Model validation

The capability of the model to represent the MPA domains consistently was assessed using methods of comparative spatial pattern recognition in order to justify the application of the model projections. In this context it is important to show the model's ability to reflect the natural ecosystem at spatial scales of the MPAs and upwards as we are not investigating the variability within one area. To this purpose model outputs of surface chlorophyll-a concentration for the present-day run were compared to monthly composites of satellite chlorophyll data from the GlobColour database (www.globcolour.info, accessed 5 March 2013) and the model error was decomposed into its spatial scale components using the wavelet method presented by Saux Picart et al. (2012). The difference between model and satellite data sets is aggregated at successively larger spatial scales and assessed at each scale using a binary map using quartile-based thresholds. The results are summarised using a skill score defined as the mean square difference relative to the mean square difference for random data: 1 represents a perfect match, 0 would be the score for matching random data and scores below 0 show that agreement is worse than random. This method of validation penalises small features which appear in one dataset but not the other, but does not over-penalise larger features which appear in both sets but slightly displaced. For both seas, the skill assessment used data for the entire model domain, where cloud-free satellite data existed, and the variability was due to differences between months.

Fig. 3 shows a boxplot summarising the skill scores for all months at all scale levels. Skill levels were consistently above 0 with the exception of the smallest scale, corresponding to one model cell (0.1°); all the areas selected to assess change in MPA conditions are at least 2 cells wide (Fig. 2). Skill levels were comparable for the two seas, though with more variability for the NE Atlantic.

As an additional validation, the Spearman rank correlation between the monthly mean modelled and satellite values at each model point was calculated for each year (n in the range 266,000–298,000, depending on domain and amount of cloud cover). Correlations were consistently around 0.5, indicating a sound representation of the spatial-temporal structure of phytoplankton biomass throughout all years.

3.2. Differences between present day and future model conditions

Table 2a and b shows the difference between present-day and future scenario data for Mediterranean MPAs under the National Responsibility (a) and Global Community (b) scenarios. Table 3a and b give similar information for North-East Atlantic MPAs. For both seas, the MPAs are arranged from west to east going down the table.

The biggest changes are seen in temperature (T), for all areas and for both scenarios. The results show a rise in annual mean sea surface temperature of 0.5–0.8 °C for most Mediterranean sites and 0.4–1.0 °C for sites in the North-East Atlantic. The index of change in mean surface temperature tends to be larger than for minimum or maximum temperature, i.e. the mean changes more than the extremes in relation to its present-day variability. Many of the sites are shallow, so that bottom level temperatures are similar to surface values, but changes are also seen at some of the deeper sites, such as Haig Fras in the North-East Atlantic and the Gulf of Lion in the Mediterranean; for both these sites the bottom-level temperature change is about the same for both scenarios, 0.3 and 0.4 °C respectively, even though the surface temperature rise is about 0.15 °C higher for the NR scenario than for GC. For MPAs in the northern parts of the Atlantic domain (East Rockall Bank, Wyville Thompson Ridge) there are more benthic temperature changes in the GC scenario than NR.

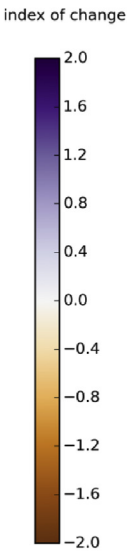
For other ecosystem indicators, there are few changes at Mediterranean sites, with some tendency towards more change in the east than the west of the region (Table 1a). The North-East Atlantic is more affected by external conditions in the wider sea (through the boundary conditions set by the GCM in this model) and by river inputs. Reduction in nutrient levels (N,P,Si) is observed both at the western sites, influenced by changes in the wider circulation, and at North Sea sites nearer river mouths. An increase in net primary production (netPP) is seen at roughly half the sites in the Mediterranean and at coastal sites in the North-East Atlantic under the NR scenario, but at very few sites for the GC scenario: sites in the western parts of the North-East Atlantic show a reduction in net primary production under the GC scenario. In spite of the greater stratification expected for warmer surface waters, there is little sign of change in the annual mean mixed layer depth (MLD) for most Mediterranean sites; the exceptions are Gulf of Lion and Isole Egadi, which show decreases in the range 4–9 m. Many of the shallower North Sea sites show a small increase in mixed layer depth, around 0.2 m, while there are decreases of a few metres for some of the deep water sites.

Reduced solubility due to higher temperatures and increased eutrophication due to higher nitrate levels can both lead to a reduction in bottom water oxygen levels (bottom O_2). This is seen at Kornati, the only Adriatic site, and for some of the North Sea MPAs, particularly under the NR scenario. At Kornati the decrease in oxygen levels is greater than that expected based on rise in temperature alone, around 2.8 mmol m^{-3}; however at the shallow North Sea sites temperature change may be enough to explain the change in oxygen levels. For sites on the NE Atlantic shelf, levels of summer chlorophyll and winter mean nitrate and phosphate were compared to the thresholds agreed by OSPAR as indicating elevated levels associated with eutrophication (OSPAR Commission, 2010). Elevated chlorophyll was not found for any MPAs, consistent with the findings of Skogen et al. (2014), but elevated nutrient levels were found at eight sites. Nutrient levels were lower under the GC scenario than under NR, and for Vlaamse Banken the difference was enough to take the concentrations below the OSPAR thresholds. No thresholds have been agreed for the Mediterranean (Garmendia et al., 2015), so the analysis was not repeated for those sites. Reduced bottom-level oxygen is also seen in the outputs for

Table 3
Difference 2040s−2000s for ecosystem indicators for North-East Atlantic MPAs (a) National Responsibility scenario (b) Global Community scenario. See Table 2 caption for details.

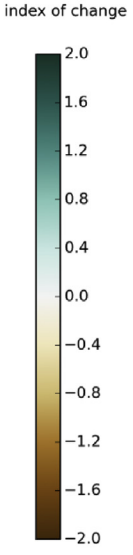
(a)

	mean surface T (°C)	max surface T (°C)	min surface T (°C)	mean bottom T (°C)	mean netPP ($mgCm^{-2}\ d^{-1}$)	mean column Zc ($mg\ C\ m^{-2}$)	mean summer Chl ($mg\ chl\ m^{-3}$)	min bottom O_2 ($mmolm^{-3}$)	mean winter N ($mmol\ m^{-3}$)	mean winter P ($mmol\ m^{-3}$)	mean winter Si ($mmol\ m^{-3}$)	mean winter N:P ratio	mean surface S (psu)	mean MLD (m)
East Rockall Bank	0.21	0.49	0.16	-0.13	-30.4	340.9	-0.032	-71.93	0.24	-0.023	-0.74	0.72	-0.08	-8.13
Hovland Mound Province	0.41	0.60	0.21	-0.62	-19.4	52.7	-0.060	-71.57	-0.54	-0.039	-0.59	0.09	-0.04	-4.28
Haig Fras	0.48	0.75	0.36	0.30	-14.8	-74.2	-0.044	0.16	-0.12	-0.037	-0.80	0.71	-0.10	-0.23
Stanton Banks	0.34	0.25	0.32	0.06	-29.6	-74.3	-0.086	-23.40	-1.00	-0.096	-1.16	1.20	-0.01	2.15
Wyville Thomson Ridge	0.16	0.17	0.25	0.03	11.9	319.0	0.050	-78.04	0.28	-0.009	-0.42	0.51	-0.05	-16.29
Iroise	0.47	0.67	0.39	0.35	6.0	-57.0	-0.003	0.58	-0.38	-0.054	-0.87	0.78	-0.11	-0.95
Cardigan Bay	0.65	0.73	0.63	0.63	15.6	2.2	0.003	-1.55	3.19	-0.036	-0.48	3.44	-0.03	0.14
Luce Bay and Sands	0.60	0.70	0.59	0.60	5.8	-5.4	-0.007	-2.82	1.56	-0.024	-0.37	1.87	-0.04	0.18
Liverpool Bay	0.79	0.88	0.76	0.78	10.9	0.3	-0.002	-2.83	5.22	-0.056	-0.69	2.19	0.03	0.18
Moray Firth SAC	0.62	0.74	0.75	0.62	-11.9	-9.5	-0.066	-0.53	1.20	-0.047	-1.11	2.43	0.14	0.52
Wight-Barfleur Reef	0.71	0.92	0.50	0.71	12.8	-0.9	-0.005	-3.07	0.24	-0.029	-0.51	1.02	-0.10	0.21
Pobie Bank Reef	0.32	0.75	0.15	0.06	-27.8	-37.6	-0.055	-29.21	0.63	0.011	-0.14	0.52	-0.18	-2.93
Margate and Long Sands	0.90	0.95	0.72	0.90	14.6	-4.5	-0.005	-2.57	2.77	-0.111	-1.16	1.87	-0.04	0.20
Vlaamse Banken	0.89	0.92	0.78	0.89	9.6	-8.6	-0.009	-2.57	0.18	-0.104	-1.17	1.96	-0.16	0.21
Norfolk Sandbanks and Saturn Reef	0.79	0.97	0.68	0.79	-12.5	-25.9	-0.036	-3.72	-0.09	-0.059	-0.83	1.32	0.04	0.20
Dogger Bank	0.76	0.89	0.76	0.76	-9.6	-44.3	-0.024	-2.89	-0.09	-0.047	-0.87	1.12	-0.00	0.15
Noordzeekustzone	0.82	0.69	0.96	0.82	9.2	1.3	-0.008	-1.94	7.79	-0.109	-0.58	3.28	0.02	0.21
Sylt.Aussenr.-Oestl.Dt.Bucht	0.97	0.73	1.11	0.93	14.5	-5.2	-0.003	-2.87	5.95	-0.125	-0.94	3.05	0.08	-0.12
Wadden sea National Park	1.10	0.78	1.50	1.10	6.2	-7.5	-0.013	-3.83	38.08	0.074	0.48	4.44	0.09	0.22
Gule Rev	0.81	0.61	0.95	0.35	31.3	-213.2	0.119	-6.29	-0.01	-0.080	-0.57	1.64	-0.75	-3.90



(b)

	mean surface T (°C)	max surface T (°C)	min surface T (°C)	mean bottom T (°C)	mean netPP ($mgCm^{-2}\ d^{-1}$)	mean column Zc ($mg\ C\ m^{-2}$)	mean summer Chl ($mg\ chl\ m^{-3}$)	min bottom O_2 ($mmolm^{-3}$)	mean winter N ($mmol\ m^{-3}$)	mean winter P ($mmol\ m^{-3}$)	mean winter Si ($mmol\ m^{-3}$)	mean winter N:P ratio	mean surface S (psu)	mean MLD (m)
East Rockall Bank	0.77	0.86	0.56	0.40	-50.0	72.6	-0.106	-61.28	-0.97	-0.064	-1.44	0.11	-0.07	6.30
Hovland Mound Province	0.35	0.40	0.27	-0.11	4.0	30.1	-0.004	-66.94	-0.15	0.004	-0.30	-0.51	-0.02	-2.39
Haig Fras	0.30	0.11	0.39	0.33	-39.1	-115.0	-0.071	2.49	-1.93	-0.144	-1.48	0.78	-0.05	-0.03
Stanton Banks	0.34	0.19	0.40	0.35	-30.1	-75.7	-0.086	-20.75	-1.05	-0.072	-0.95	0.34	0.03	2.07
Wyville Thomson Ridge	0.48	0.25	0.56	0.47	8.7	134.9	0.041	-73.03	-0.05	-0.019	-0.84	0.31	-0.05	-9.16
Iroise	0.52	0.53	0.49	0.48	-37.9	-124.3	-0.065	-2.81	-1.63	-0.132	-1.26	0.96	-0.07	-0.08
Cardigan Bay	0.34	0.12	0.44	0.33	0.6	-9.9	-0.002	-1.53	-2.07	-0.208	-1.52	2.36	0.04	0.24
Luce Bay and Sands	0.34	0.26	0.38	0.34	1.8	-5.2	-0.001	-1.18	-2.11	-0.211	-1.51	1.55	0.07	0.23
Liverpool Bay	0.37	0.09	0.50	0.37	1.8	-3.2	-0.003	-1.17	-2.18	-0.594	-1.55	2.44	0.11	0.20
Moray Firth SAC	0.44	0.20	0.62	0.56	-8.3	-9.7	-0.021	2.47	-1.11	-0.088	-1.15	0.77	0.09	0.45
Wight-Barfleur Reef	0.37	0.21	0.46	0.37	-5.8	-38.0	-0.009	-1.19	-1.93	-0.153	-1.27	1.03	-0.05	0.23
Pobie Bank Reef	0.41	0.19	0.57	0.40	-10.8	-25.9	-0.018	-31.33	0.64	0.015	-0.47	0.44	-0.11	-1.01
Margate and Long Sands	0.48	0.15	0.63	0.48	5.9	-2.6	-0.005	-0.60	-2.32	-0.593	-1.68	2.36	0.01	0.22
Vlaamse Banken	0.45	0.06	0.62	0.45	0.0	-8.8	-0.010	0.12	-3.03	-0.290	-1.84	2.08	0.00	0.22
Norfolk Sandbanks and Saturn Reef	0.46	0.35	0.53	0.46	-14.5	-16.8	-0.036	-1.87	-0.56	-0.051	-0.66	0.41	-0.01	0.22
Dogger Bank	0.49	0.26	0.66	0.49	-28.4	-49.1	-0.047	-1.41	-0.73	-0.053	-0.85	0.21	-0.00	0.24
Noordzeekustzone	0.49	0.32	0.67	0.49	3.5	-0.1	-0.008	-1.47	-2.68	-0.721	-1.31	4.25	0.05	0.22
Sylt.Aussenr.-Oestl.Dt.Bucht	0.62	0.39	0.96	0.62	0.5	-13.9	-0.012	-1.46	-3.48	-0.586	-1.64	3.79	0.09	0.27
Wadden sea National Park	0.70	0.43	1.18	0.70	0.0	-9.1	-0.016	-2.00	-1.91	-1.851	-1.12	5.37	0.06	0.22
Gule Rev	0.65	0.55	1.06	0.54	-6.0	-153.7	0.014	-4.77	-0.67	-0.086	-0.56	0.95	-0.47	-3.26



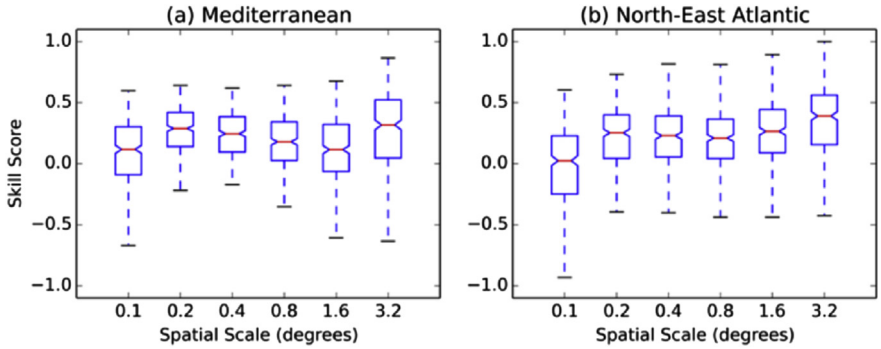


Fig. 3. Model skill at different spatial scales (degrees) against GlobColour satellite chlorophyll, derived from wavelet analysis (<0:poor, >0 good, 1 = perfect match). (a) Mediterranean (b) North-East Atlantic. Each bar represents the average score for 120 months.

western sites in the North-East Atlantic, of order 60–80 mmol m^{-3} at East Rockall Bank, Hovland Mound Province and Wyville Thompson Ridge: here temperature changes only account for a change of at most 10 mmol m^{-3}. The reduced oxygen levels may be a cause for concern given the sensitive benthic ecosystem of these deep-water sites.

In general, there is more change in the National Responsibility than Global Community scenario: higher increases in temperature and a greater number of significant changes in other variables. In the Mediterranean the increase in mean surface temperature is around 0.1–0.15 °C higher under the NR scenario for most sites except those in the far east, where the differences between scenarios are small (see the last four rows in Table 2a,b). For the NE Atlantic the difference between scenarios is 0.2–0.5 °C for most sites; here the exception is the west, where the differences are smaller and East Rockall Bank has a 0.5 °C *lower* increase under the NR scenario. The other exception to the general pattern of larger changes under the NR scenario is nutrient levels in the North-East Atlantic, where the effect of reductions in river loadings can be seen especially in the reduced phosphate levels in the GC scenario, down by 0.1–0.2 mmol m^{-3} at most MPAs and more near river mouths, and corresponding increases in the N:P ratio.

The above results all consider annual values and so do not consider changes in seasonality. Monthly mean data was examined for changes in intra-annual variation between present and future conditions. There were small shifts in a few cases, but no consistent patterns were found.

To put the changes in the MPAs into the wider context, the change in surface temperature was plotted across the whole domain for each sea and each scenario (Fig. 4). In general the pattern of change is similar for the NR and GC results, with greater increases for the NR scenario. The exception is the Atlantic area to the north and west of the British Isles, as already noted for MPAs in that region: there are few significant changes for the NR scenario, but some temperature rises for the GC scenario. In the Mediterranean the greatest increases are seen in the Adriatic and to the south of Sicily; in the North-East Atlantic the biggest changes occur at the shelf break and around Norway, there are also greater than average changes in the eastern North Sea. This presentation of a single variable across a wide spatial area contrasts with the multiple-indicator, spatially aggregated view shown in Tables 1 and 2. The approaches are complementary, but here our focus is on the multi-indicator view.

4. Discussion

Results from a regional model have been used to produce multi-indicator projections of change between the 2000s and the 2040s under two scenarios of climate change and river management. Tables 2 and 3 give an overview of how conditions in a sample of Marine Protected Areas may change. Changes in temperature occur at all locations, but changes in other indicators vary from place to place, demonstrating that temperature is not adequate as a proxy for all change. Even within temperature, patterns of minimum and maximum surface temperature and of benthic temperature differ from the mean: a multi-indicator view is needed to capture the wider picture of projected change.

The case study presented here is for two contrasting European seas, the Mediterranean and the North-East Atlantic. In the Mediterranean, more changes across multiple indicators were seen in eastern than western sites (Table 2a). This is to be welcomed in the light of the greater biodiversity currently found in the west of the sea (Coll et al., 2010), but it also highlights the need for greater attention to the eastern region, particularly as higher temperatures here may enable invasive species arriving from the Suez Canal to survive and spread (Coll et al., 2010). There are currently many fewer MPAs in the east and those that have been established are small and not well connected (Gabrié et al., 2012): they are unlikely to be sufficient to act as refuge sites for species challenged by rising temperatures as well as other stressors. Further MPAs are needed and model results for the wider area can be a useful tool in the selection of suitable sites. Fig. 4 shows some areas of the eastern Mediterranean where the rise in surface temperature is lower than average, and similar plots for other ecosystem indicators could further assist in MPA location.

The north-western part of the Mediterranean has a key role to play as warming drives species north from their current range. This area already has a number of reserves, including the Gulf of Lion, Calanques and the Pelagos Sanctuary in the current study: of these, the Gulf of Lion is projected to have the largest changes in mean and extreme sea surface temperature; this MPA is discussed further below. The Adriatic could be another refuge site for cool-water species, but the projections show it increasing in temperature more than other areas (Fig. 4a,b). In addition, the results for Kornati (Table 2 and Section 3.2) suggest that eutrophication could continue to be a problem in this already affected region if controls on river nutrients are not put in place.

The NE Atlantic is more open to the influence of the wider ocean than the Mediterranean, and this is apparent in the projections for the north-west of the region (East Rockall Bank, Wyville Thompson Ridge, Stanton Banks). These are projected to experience changes in most indicators studied (Table 3) and, unlike all other areas, the changes are greater under the GC scenario than under the higher emission NR scenario. This is because of differences in the position of the North Atlantic Current in the GCM under the NR and GC scenarios, with the Gulf Stream directed further to the south for NR;

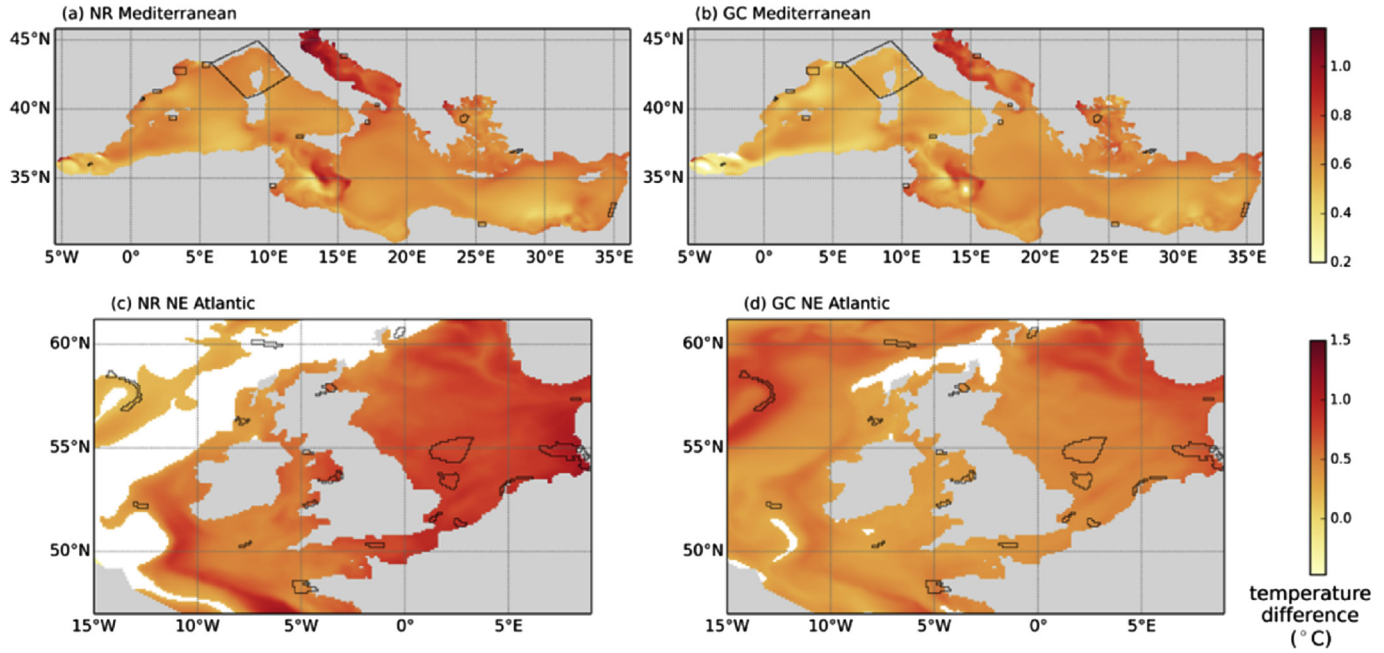


Fig. 4. Change in annual mean surface temperature from present-day values for (a,b) the Mediterranean and (c,d) the North-East Atlantic model domain. (a,c) results for National Responsibility scenario; (b,d) results for Global Community scenario. Points where the difference between present and future runs was not significant ($p > 0.05$) are shown in white. MPAs discussed in this paper are outlined in black.

such differences in North Atlantic circulation have also been observed between different GCMs (Randall et al., 2007). Hence MPAs in this region may be particularly sensitive to climate change and uncertainty is high: monitoring of environmental conditions and more focussed modelling studies are recommended. Pobie Bank Reef, in the northern North Sea, is also affected by these circulation changes. Benthic oxygen levels are projected to decrease and this could affect the northward movement of species in a warming sea, even though this sea lacks the physical boundary present in the Mediterranean.

Comparing the two seas, the Mediterranean ecosystem seems more resilient: changes in temperature occur everywhere, but there are relatively few changes in other indicators, especially in the GC scenario. The picture is more varied in the North-East Atlantic, with different patterns of change for the North Sea and the deep water regions to the north and west. The North Sea results show the influence of rivers, with nutrient levels falling especially under the GC scenario, while the north and west are dominated by the influence of the open ocean and so depend on the circulation patterns projected by the GCM.

The projections presented here are most useful for considering regional environmental change and the impact on networks of MPAs. However, they can also give insights into policy guidance for individual MPAs: to illustrate this we briefly consider how they could be applied to four MPAs, located across the region and set up for a variety of reasons.

The Hovland Mound Province Special Area of Conservation (NE Atlantic) was set up under the EU Habitats Directive to protect its reefs – in this case carbonate mounds colonised by cold water corals, which are recognised by OSPAR as a threatened habitat requiring protection (OSPAR, 2010). Reefs are directly vulnerable to change in environmental conditions at the sea bed and also to changes higher in the water column affecting primary production and hence the food supply to deeper water. Our projections show cooling and sharp decreases in oxygen at the sea bed, especially under the NR scenario. At the surface, temperatures rise and nutrients decline, overall there is no change in primary production. Advice to OSPAR, based on general expectations for climate change, suggests that there may be shifts in productivity and hence in the food supply to benthic organisms, but does not mention decline in oxygen levels (OSPAR, 2010): the contrast with our projections demonstrates the value that regional modelling can add to more general understanding of change. If changes in environmental conditions threaten the corals a move of the MPA may be indicated; however this may be difficult given the limited spatial extent of carbonate mounds. Common monitoring procedures for this MPA and other coral carbonate mounds further to the north (e.g. NW Porcupine Bank SAC, not included in this study) would improve understanding of the link between environmental conditions and coral health and facilitate early identification of climate-related change.

Margate and Long Sands Special Area of Conservation (North Sea) was also set up under the Habitats Directive, in this case as an example of sandbanks covered at all times. The fauna includes commercially important species such as sole and herring. Conservation advice (Natural England, 2012) includes the effects of physical loss and damage, contamination and biological disturbance but does not mention climate change. Under the NR scenario we project a mean temperature rise of almost 1 °C throughout the water column in this shallow water location: we recommend that environmental monitoring should include looking for signs of temperature stress and/or change in community structure consistent with rising temperatures. It is also worth noting that, although not included in the current model, sea level rise and changes in storminess will affect water depth and sediment movement in this estuary-mouth environment.

As noted, above, the Gulf of Lion MPA (Parc Marin du Golfe du Lion) is projected to have the largest temperature changes in the north-west Mediterranean. The MPA was created to protect its wide biodiversity, with habitats including seagrass beds, muddy shelf areas and submarine canyons and a number of protected species such as red corals and cetaceans. Its management guidelines are

broadly drawn and include sustainable socio-economic development and conservation of maritime heritage as well as well as protection of marine ecosystems (www.parc-marin-golfe-lion.fr, accessed 1 February 2016). Attention to watersheds is explicitly included and this is supported by our projections, which show rising nitrogen and primary production under the NR scenario but no significant change under GR. A decrease in the mixed layer depth suggests greater stratification associated with surface warming. Temperature rises in the order of 0.4–1.0 °C are projected, and with some fish already shown to be moving northwards as the seas warm (Sabatés et al., 2006; Maynou et al., 2014) new species must be expected in the MPA. If monitoring shows that existing species are under threat from new competitors or thermal stress a further protected area may be needed. Our projections show a region of lower temperature rise to the east of the MPA, between Gulf of Lion and Calanques MPAs (Fig. 4), and this could be investigated for suitability.

As a final example, the National Marine Park of Alonissos, Northern Sporades (eastern Mediterranean) was set up to provide protection for a single endangered species, the Mediterranean monk seal, which is threatened by human activities including fishing and tourism (Karamanlidis et al., 2004). Our projections show higher temperatures and, for the NR scenario, increased nutrients and primary production. Higher productivity could potentially benefit the seal if the temperature rise is not out of its range of tolerance and fisheries are controlled; the maximum projected temperature rise of 1 °C leaves conditions cooler than present-day Crete, where seals are currently found (Karamanlidis and Dendrinos, 2015). The projections suggest that it would be wise to monitor environmental conditions, but managing the direct human threat is probably more important in this case.

These examples show how projections at the regional scale can put individual MPAs into their environmental context and indicate how that context may change under contrasting scenarios of wider emissions changes; hence they can play a part in indicating vulnerability and deciding where resources should be used to monitor conditions and investigate future impacts more fully. However, they cannot resolve the fine detail of local conditions, for example the canyons of the Gulf of Lion or the shallow waters of Margate and Long Sands, and they may be less accurate close to the coast than in open water; plans at the local level should be based on tailored projections using a model appropriate to the local environment. For example, given the importance of the Gulf of Lion area as a refuge for cold-water species and its vulnerability as shown by this work, high-resolution modelling of the whole area should be considered as part of future planning. In addition, detailed knowledge of the biology of locally-important species is needed in order to understand the potential impacts of environmental change: response to temperature change is often not linear and change in other variables can add further complexity (e.g. Maynou et al., 2014).

Extension of the current work could include the use of other indicators, such as biomass for higher trophic levels and a measure of larval distribution distance and/or connectivity to neighbouring MPAs. Inclusion of pH would allow ocean acidification to be investigated. For a full implementation, a wider range of forcing data should be tested, taken from a range of GCMs and using up to date emissions scenarios.

Regional projections of climate change impacts are subject to substantial uncertainties. We have given a first indication of one aspect of this uncertainty by projecting scenarios of contrasting mitigation strategy. To develop the approach into an operational tool for management and decision support more in-depth simulations would be required in order to deliver a comprehensive quantification of the uncertainties in the provided estimates.

The results presented here back up other work in suggesting that there is no simple formula which can be applied to all MPAs (Jones et al., 2013; Otero et al., 2013). Understanding potential change, both qualitatively and quantitatively, is an important step in building a resilient network that can adapt to future conditions. Multi-indicator projections from regional models can help to show which reserves are vulnerable to change and may need further attention and resources.

5. Conclusion

Regional models can provide projections of change in multiple ecosystem indicators for a given spatial area. This multi-indicator view complements spatially-resolved information about a single variable, which has more traditionally been used, giving an overview of projected change for a given MPA. We have illustrated this approach for MPAs in two European seas, showing that vulnerable areas can be indicated and particular MPAs identified for further study or action. In particular, the results highlight the vulnerability of potential refuge sites in the north-west Mediterranean and the need for careful monitoring at MPAs to the north and west of the British Isles, which may be affected by changes in Atlantic circulation patterns. The projections also support the need for more MPAs in the eastern Mediterranean and Adriatic Sea, and can provide information about present and future environmental conditions to assist with site selection.

The results quantify the difference that can be expected under two scenarios of climate change and river management and demonstrate the effect that mitigation through reduced emissions could have. Models have an increasing role to play in planning for and managing MPAs under climate change and other non-local stressors: this study has demonstrated a way to make use of the wide range of data available from coupled physical-biogeochemical-ecosystem models to help ensure that MPAs will be fit for purpose in the future.

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